

# Search for QGP and Thermal Freeze-out of Strange Hadrons

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After reviewing the observables of QGP we perform an analysis of  $m_{\perp}$  spectra of strange hadrons measured as function of centrality in 156A GeV Pb–Pb interactions. We show that there is a good agreement between the chemical and thermal freeze-out conditions, providing additional evidence for the formation and sudden disintegration of a super cooled QGP fireball.

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## I. QUARK MATTER IN LABORATORY

The development of the quark model has been from the first moments accompanied by consideration of the transition from a few body hadronic bound state to a many body quark matter star formation [1]. This was followed by the development of the quantum many body theory of quark matter [2,3], which lead on to the formal recognition within the framework of QCD that perturbative quark matter state must exist [4], given the asymptotically free nature of theory of strong interactions, quantum-chromodynamics (QCD). Arguments arising from study of a dense hadron gas within the scheme of Hagedorn's statistical bootstrap and the resulting boiling of hadronic matter lead from a different direction to the consideration of the transition to a hadron substructure phase [5]. In short, the quark-gluon plasma (QGP) as we today call hot quark matter has been for 30 years an expected new state of matter.

The nuclear physics establishment considered at that time, if not still today, other ideas about new phases of matter which could be formed in relativistic nuclear collisions, to be of greater interest. It is interesting to recall here that in the first of the series of formative workshops in the field of relativistic heavy ion collisions, the "Bear Mountain" meeting convoked in November 1974 there is not a single mention of quarks, let alone of quark matter. At the time "Lee-Wick" ultra dense nuclei, pion condensates, multi-hyperon nuclear states were considered as the discovery potential of these new and coming tools of nuclear physics research.

As the ideas about QGP formation in high energy nuclear collisions matured [6], a challenge emerged how the locally deconfined state which exists a mere  $10^{-22}$ s can be distinguished from the gas of confined hadrons. This is also a matter of principle, since arguments were advanced that this may be impossible since both quark and hadron pictures of the reaction are equivalent. Therefore a quark-gluon based description is merely a change of Hilbert space expansion basis.

Clearly these difficult questions can be settled by an experiment, if a probe of QGP operational on the collision time scale, can be devised. There were three major groups of observables proposed, and we address these in

the chronological order of their appearance in literature.

Dileptons, direct Photons: The study of multi particle production phenomena has stimulated the exploration of dileptons and photons as the probe of dense hadron matter fireballs, which ideas were easily adapted to the QGP phase situation. After the seminal work of Feinberg [7] and Shuryak [8] a comprehensive discussion of this observable was offered [9].

However, since electromagnetic currents are the source of photons and dileptons, both confined and deconfined dense elementary hadron matter can produce these electromagnetic probes. The principal novel component of QGP, gluons, are not a required ingredient.

On practical side, the backgrounds are very significant. The photon production is dominated by factor 10-20 larger  $\pi^0$  decay, and dileptons arise in decays of vector mesons which are also abundantly produced in multi particle production processes, irrespective if the formation of QGP has occurred or not. Thus electromagnetic signature of QGP has to be extracted comparing in a detailed and quantitative study experiment with theory.

Such a comparison is extremely difficult unless we have good data and already know at what condition QGP has been formed and how it evolved. But present day experiments suffer both from systematic acceptance issues, and low statistics. In our view, the electromagnetic probes will come of age as a second generation diagnostic tools in the refinement of the study of the QGP phase properties.

Strangeness enhancement: One aspect of this probe of QGP will be addressed in this paper. The ideas about enhancement are simple: when color bonds are broken the chemically (abundance) equilibrated deconfined state has an unusually high abundance of strange quarks [10]. Subsequent study of the dynamical process of chemical equilibration has shown that only the gluon component in the QGP is able to produce strangeness rapidly [11], allowing formation of (nearly) chemically equilibrated dense phase of deconfined, hot, strangeness-rich, quark matter in relativistic nuclear collisions. Therefore strangeness enhancement is related directly to presence of gluons in QGP.

The high density of strangeness formed in the reaction fireball favors formation of multi strange hadrons [12,13],

which are produced rarely if only individual hadrons collide [14,15]. In particular a large enhancement of multi strange antibaryons has been proposed as characteristic and nearly background-free signature of QGP [12]. Such a systematic enhancement has in fact been observed, rising with strangeness content [16].

Although conventional theoretical models were explored to interpret the strangeness signatures of new physics [17], we are not aware of a consistent interpretation of the data other than in the context of QGP formation. Experimental results are abundant and allow a precise diagnosis of the chemical freeze-out conditions [18], and an assessment about the initial conditions [19].

**Charmonium:** By the time the CERN experiment NA38 was taking data on Charmonium production in nuclear collisions, the possibility that formation of QGP will influence the final state yield of charmonium has been raised [20]. This important topic has undergone a significant evolution over the past 15 years. In fact the originally predicted charmonium suppression at SPS energy can turn to a charmonium enhancement at RHIC energies. By virtue of detailed balance, both dissociation and QGP based charmonium production channels must be considered. A requirement for dominating enhancement effect is a sufficient number of available open charm quark pairs in the QGP [21].

Based on these diverse experimental signatures, it is believed that a new form of matter, presumably quark matter, has been formed in relativistic nuclear collision experiments carried out at CERN-SPS [22]. Detailed analysis of strangeness production results in addition implies that a dense fireball of matter formed in these reactions expands explosively, super cools, and in the end encounters a mechanical instability which facilitates sudden break up into hadrons [23].

For the study presented in this paper the key point is that when sudden QGP breakup occurs, the spectra of hadrons are not formed at a range of stages in fireball evolution, but arise rather suddenly. Most importantly, particles of very different properties are produced by the same mechanism and thus are expected to have similar  $m_{\perp}$ -spectra as is indeed observed [24]. The reported symmetry of the strange baryon and antibaryon spectra is strongly suggesting that the same reaction mechanism produces  $\Lambda$  and  $\bar{\Lambda}$  and  $\Xi$  and  $\bar{\Xi}$ . This is a surprising, but rather clean experimental fact, which we will interpret quantitatively in this paper.

When the momentum distributions of final state particles stop evolving during the fireball evolution, we speak of thermal freeze-out. Because a spectrum of strange hadrons includes directly produced, and heavy resonance decay products, one can determine the freeze-out temperature and dynamical velocities of fireball evolution solely from the study of precisely known shape of the particle spectra. We demonstrate this in some detail in section IV. The physical mechanism is that the freeze-out temperature determines the relative contribution of each decaying resonance while the shape of each decay contri-

bution differs from the thermal shape, see section II.

We note that we make in our analysis the tacit assumption that practically all decay products of resonances are thermally not re-equilibrated, which is equivalent to the assumption of sudden freeze out. This is consistent with our finding that the  $m_{\perp}$  strange baryon and antibaryon distributions of  $\Lambda, \bar{\Lambda}, \Xi, \bar{\Xi}$  froze out near to the condition at which the chemical particle yields were established.

One of the key objectives of this work is to present a comparison between thermal and chemical freeze-out analysis results for temperature, (explosion) collective velocity and other chemical and dynamical parameters. It is important to realize that particle spectra and yields are sensitive to magnitude of collective matter flow, in which produced particles are born, for somewhat different reasons: 1) in thermal analysis the collective flow combines with thermal freeze-out temperature to fix the shape of each particle spectrum, and temperature is also controlling the relative yield of contributing resonances – see previous paragraph for a here relevant tacit assumption – thus both  $T$  and  $v$  are fixed by the shape of  $m_{\perp}$  data; 2) in chemical analysis the particle yields required are obtained integrating spectral yields, with experimental acceptance in  $p_{\perp}, y$  implemented [18]. Since many particles have a too small particle momentum to be usually observed, the acceptance-cut yields used in chemical analysis depend quite sensitively on parameters which deform the soft part of the spectra without changing the number of produced particles, such as is the flow velocity. For this reason precise particle spectra and yields are allowing to draw conclusions about the proximity of thermal and chemical freeze-out conditions.

## II. THERMAL FREEZE-OUT ANALYSIS

In recent months experiment WA97 determined the absolute normalization of the published  $m_{\perp}$  distribution [24], and we took the opportunity to perform the spectral shape analysis and will compare our results to those obtained in chemical yield analysis [18] in order to check if the thermal and chemical freeze-out conditions are the same. Our analysis continues and this report gives its current status.

We report here a simultaneous analysis of absolute yield and shape of WA97 results of six  $m_{\perp}$ -spectra of  $\Lambda, \bar{\Lambda}, \Xi, \bar{\Xi}, \Omega + \bar{\Omega}, K_s = (K^0 + \bar{K}^0)/2$  in four centrality bins. If thermal and chemical freeze-outs are identical, our present results must be consistent with earlier chemical analysis of hadron yields. Since the experimental data we here study is dominated by the shape of  $m_{\perp}$ -spectra and not by relative particle yields, our analysis is de facto comparing thermal and chemical freeze-outs.

We have found, as is generally believed and expected, that all hadron  $m_{\perp}$ -spectra are strongly influenced by resonance decays. Thus we apply standard procedure to allow for this effect [25,26]. The final particle distribu-

tion is composed of directly produced particles and decay products:

$$\frac{dN_X}{dm_\perp} = \frac{dN_X}{dm_\perp}|_{\text{direct}} + \sum_{\forall R \rightarrow X+2+\dots} \frac{dN_X}{dm_\perp}|_{R \rightarrow X+2+\dots} \quad (1)$$

Here:  $R(M, M_T, Y) \rightarrow X(m, m_T, y) + 2(m_2) + \dots$ , where we indicate by the arguments that only for the decay particle  $X$  we keep the information about the shape of the momentum spectrum. We consider here only the 2-body decay as no other contributing decays are known for hyperons, and hard kaons. In detail, the decay contribution to yield of  $X$  is:

$$\frac{dN_X}{dm_\perp^2 dy} = \frac{g_r b}{4\pi p^*} \int_{Y_-}^{Y_+} dY \int_{M_{T_-}}^{M_{T_+}} dM_T^2 J \frac{d^2 N_R}{dM_T^2 dY} \quad (2)$$

$$J = \frac{M}{\sqrt{P_T^2 p_T^2 - \{ME^* - M_T m_T \cosh \Delta Y\}^2}}$$

We have used  $\Delta Y = Y - y$ , and  $\sqrt{s}$  is the combined invariant mass of the decay products other than particle  $X$  and  $E^* = (M^2 - m^2 - m_2^2)/2M$ ,  $p^* = \sqrt{E^{*2} - m^2}$  are the energy and momentum of the decay particle  $X$  in the rest frame of its parent. The limits on the integration are the maximum values accessible to the decay product  $X$ :

$$Y_\pm = y \pm \sinh^{-1} \left( \frac{p^*}{m_T} \right)$$

$$M_{T_\pm} = M \frac{E^* m_T \cosh \Delta Y \pm p_T \sqrt{p^{*2} - m_T^2 \sinh^2 \Delta Y}}{m_T^2 \sinh^2 \Delta Y + m^2}$$

The theoretical primary particle spectra (both those directly produced and parents of decay products) are derived from the Boltzmann distribution by Lorentz-transforming from a flowing intrinsic fluid element to the CM-frame, and integrating over allowed angles between particle direction and local flow.

We introduce two velocities: a local flow velocity  $v$  of fireball matter where from particles emerge, and hadronization surface (breakup) velocity which we refer to as  $v_f^{-1} \equiv dt_f/dx_f$ . Particle production is controlled by the effective volume element, which comprises

$$dS_\mu p^\mu = d\omega \left( 1 - \frac{\vec{v}_f^{-1} \cdot \vec{p}}{E} \right), \quad d\omega \equiv \frac{d^3 x d^3 p}{(2\pi)^3}. \quad (3)$$

The Boltzmann distribution we adapt has thus the form

$$\frac{d^2 N}{dm_T dy} \propto \left( 1 - \frac{\vec{v}_f^{-1} \cdot \vec{p}}{E} \right) \gamma m_T \cosh y e^{-\gamma \frac{E}{T} (1 - \frac{\vec{v} \cdot \vec{p}}{E})}, \quad (4)$$

where  $\gamma = 1/\sqrt{1-v^2}$ .

The normalization for each hadron type  $h = X, R$  is

$$N^h = V_{\text{QGP}} \prod_{i \in h}^n \lambda_i \gamma_i$$

Here we use the chemical parameters  $\lambda_i, \gamma_i$   $i = q, s$  which are as defined in [18]. and commonly used to characterize relative and absolute abundances of light and strange quarks.

Since particle spectra we consider have a good relative normalization, only one parameter is required for each centrality in order to describe the absolute normalization of all six hadron spectra. This is for two reasons important:

a) we can check if the volume from which strange hadrons are emitted grows with centrality of the collision as we expect;

b) we can determine which region in  $m_\perp$  produces the excess of  $\Omega$  noted in the chemical fit [18] is coming from.

However, since the normalization  $V_{\text{QGP}}$  common for all particles at given centrality comprises additional experimental acceptance normalization, we have not determined the value of the fireball emission volume at each centrality. Hence we will be presenting the volume parameter as function of centrality in arbitrary units.

The best thermal and chemical parameters which minimize the total relative error  $\chi_T^2$  at a given centrality:

$$\chi_T^2 = \sum_i \left( \frac{F_i^{\text{theory}} - F_i}{\Delta F_i} \right)^2,$$

for all experimental measurement points  $F_i$  having measurement error  $\Delta F_i$  are determined by considering simultaneously for results of experiment WA97 [24] i.e.  $K^0, \Lambda, \bar{\Lambda}, \Xi, \bar{\Xi}, \Omega + \bar{\Omega}$ . We have checked the validity of the statistical analysis by the usual method, i.e. omission of some data in the fit.

Only in case of Kaons we find any impact of such a procedure. Noting that the statistical error of kaon spectra is the smallest, we have established how a systematic error which could be for Kaons greater than statistical error would influence our result. For this purpose we assign to  $K^0$  experimental results in most of our analysis an ‘error’ which we arbitrarily have chosen to be 5 times greater than the statistical error. In this way the weight of the kaon spectra in the analysis is greatly reduced. In the first result figure below (figure 1) we present both results, standard  $K^0$  error and enlarged error. We see that while in individual result some change can occur, overall the physical result of both analysis are consistent. Thus we can trust in the combined study of hyperon and kaon data. This conclusion is reaffirmed in section IV, where we will see that the minimization of  $\chi_T^2$  involve more or less pronounced minima, depending on the error size of the kaon spectra, see Fig. 11. In most calculations we present in this paper we will be using, unless otherwise said, hyperon results combined with the Kaon data with 5 times enlarged statistical error. We believe that in this way we will err on the conservative side in our physical conclusions.

### III. OVERVIEW OF THE RESULTS

We show here a slate of results obtained within the approach outlined above. First we address the parameters determining the shape of the  $m_\perp$  distributions, that is  $T, v, v_f$ .

As function of the centrality bin we show in Fig. 1 the freeze-out temperature  $T$  of the  $m_\perp$  spectra. The horizontal lines delineate range of result of the most recent chemical freeze-out analysis, see Ref. [18].

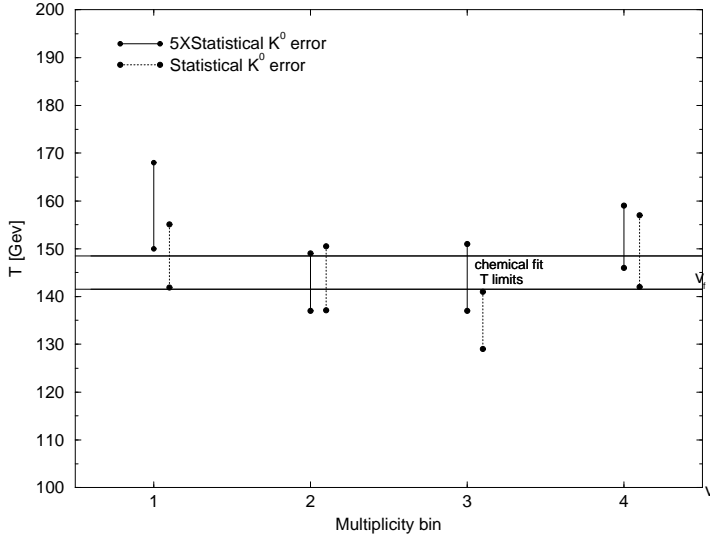


FIG. 1. Thermal freeze-out temperature  $T$  for different centrality bins compared to chemical freeze-out analysis shown by horizontal solid lines. Original statistical error is used in the dotted results, five times statistical error for kaon data is used in solid vertical lines, see text.

It is reassuring that we find a result consistent with the purely chemical analysis of data that included non-strange hadrons [18]. There is no indication of a significant or systematic change of  $T$  with centrality. This is consistent with the believe that the formation of the new state of matter at CERN is occurring in all centrality bins explored by the experiment WA97. Only most peripheral interactions produce a change in the pattern of strange hadron production [27]. The (unweighted) average of all results shown in Fig. 1 produces a freeze-out temperature at the upper boundary of the pure chemical freeze-out analysis result,  $T \simeq 145$  MeV. It should be noted that in chemical analysis  $v_f = v$  [18], which may be the cause of this slight difference between current analysis average and the earlier purely chemical analysis result.

The magnitudes of the collective expansion velocity  $v$  and the break-up (hadronization) speed parameter  $v_f$  are presented in Fig. 2. For  $v$  (lower part of the figure) we again see consistency with earlier chemical freeze-out analysis results, and there is no confirmed systematic trend in the behavior of this parameter as function of centrality.

Though within the experimental error, one could argue inspecting Fig. 2 that there is systematic increase in transverse flow velocity  $v$  with centrality and thus size of the system. This is expected, since the more central events comprise greater volume of matter, which allows more time for development of the flow. Interestingly, it is in  $v$  and not  $T$  that we find the slight change of spectral slopes noted in the presentation of the experimental data [24].

The value of the break-up (hadronization) speed parameter  $v_f = 1/(\partial t_f / \partial r_f)$  shown in the top portion of Fig. 2 is near to velocity of light which is highly consistent with the picture of a sudden breakup of the fireball. This hadronization surface velocity  $v_f$  was in the earlier chemical fit set to be equal to  $v$ , as there was not enough sensitivity in purely chemical fit to determine the value of  $v_f$ .

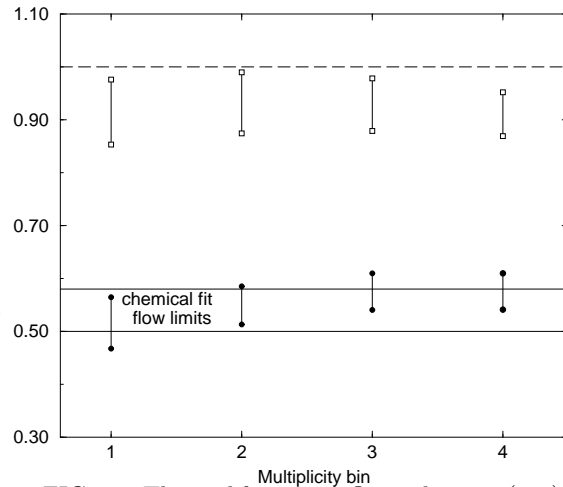


FIG. 2. Thermal freeze-out flow velocity  $v$  (top) and break up (hadronization) velocity  $v_f$  for different centrality bins. Upper limit  $v_f = 1$  (dashed line) and chemical freeze-out analysis limits for  $v$  (solid lines) are also shown.

Unlike the temperature and two velocities, the overall normalization of hadron yields,  $V^h$  must be, and is strongly centrality dependent, as is seen in Fig. 3. This confirms in quantitative way the believe that the entire available fireball volume is available for hadron production. The strong increase in the volume by factor 6 is qualitatively consistent with a geometric interpretation of the collision centrality effect. Not shown is the error propagating from the experimental data which is strongly correlated to the chemical parameters discussed next. This systematic uncertainty is another reason we do not attempt an absolute unit volume normalization.

The 4 chemical parameters  $\lambda_q, \lambda_s, \gamma_q, \gamma_s/\gamma_q$  are shown in the following Figures 4,5. These parameters determine along with  $V^h$  the final particle yield. Since we have 5 parameters determining normalization of 6 strange hadron spectra, and as discussed we reduce the statistical weight of Kaons, there is obviously a lot of correlation between these 4 quantities, and thus the error bar which reflects

this correlation, is significant.

The chemical fugacities  $\lambda_q$  and  $\lambda_s$  shown in Fig. 4 do not exhibit a systematic centrality dependence. This is consistent with the result we found for  $T$  in that the freeze-out properties of the fireball are seen to be for the temperature and chemical potential values independent of the size of the fireball. Comparing to the earlier chemical freeze-out result in Fig. 4 one may argue that there is a systematic downward deviation in  $\lambda_q$ . However, this could be caused by the fact that the chemical freeze-out analysis allowed for isospin-asymmetric  $\Xi^-(dss)$  yield [18], while our present analysis is not yet distinguishing light quarks.

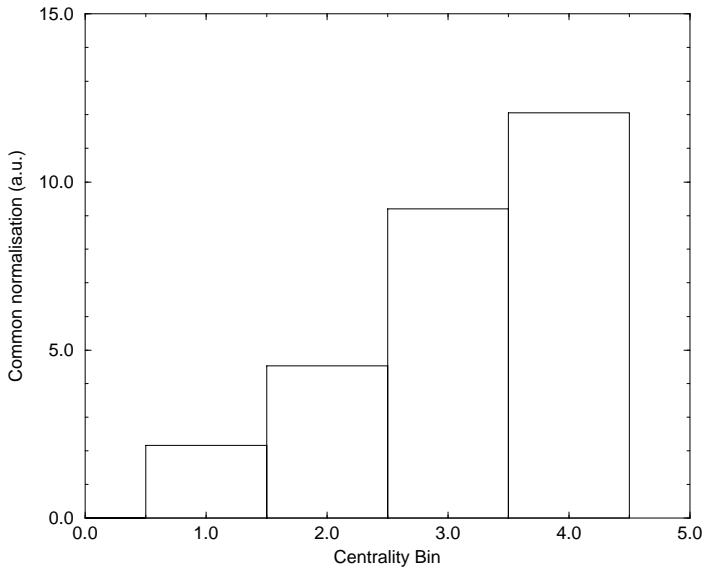


FIG. 3. Hadronization volume (arbitrary units) for different centrality bins.

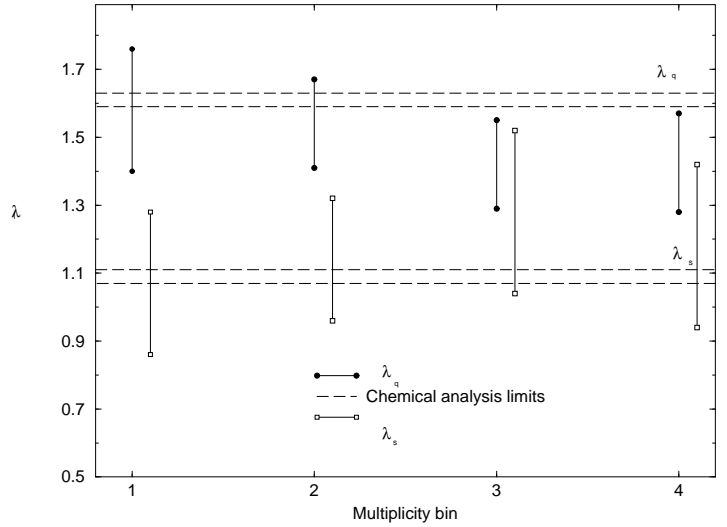


FIG. 4. Thermal analysis chemical quark fugacity  $\lambda_q$  (top) and strange quark fugacity  $\lambda_s$  (bottom) for different centrality bins compared to the chemical freeze-out analysis results.

The ratio  $\gamma_s/\gamma_q$  shown in bottom portion of Fig. 5 is systematically smaller than unity, consistent with many years of prior analysis: when  $\gamma_q = 1$  is tacitly chosen, this ratio is the value of  $\gamma_s$  in analysis of strange baryons. We have not imposed a constrain on the range of  $\gamma_q$  (top of Fig. 5) and thus values greater than the pion condensation point  $\gamma_q^* = e^{m_\pi/2T} \simeq 1.65$  (thick line) can be expected, but in fact do not arise.

It is important to explicitly check how well the particle  $m_\perp$ -spectra are reproduced. We group all bins in one figure and show in Figs. 6, 7, 8, 9 in sequence  $\Lambda$ ,  $\bar{\Lambda}$ ,  $\Xi$ ,  $\bar{\Xi}$ . It is important to note that there are some significant deviations which appear to be falling outside of the trend set by the other measurements. —this occurs for  $\Lambda$  as well but remains invisible in the figure due to the smallness of the experimental error bar. Overall, the description of the shape of the spectra is very satisfactory.

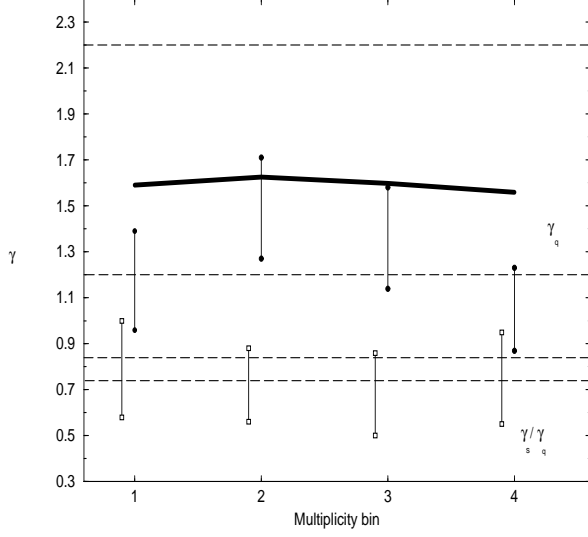


FIG. 5. Thermal analysis chemical quark abundance parameter  $\gamma_q$  (top) and  $\gamma_s/\gamma_q$  (bottom) for different centrality bins compared to the chemical freeze-out analysis. Thick line: upper limit due to pion condensation.

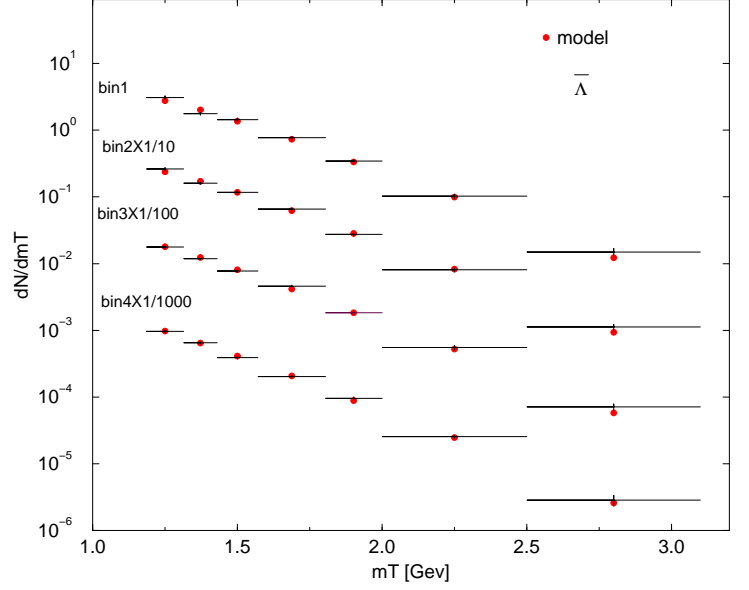


FIG. 7. Thermal analysis  $m_T$  spectra:  $\bar{\Lambda}$ .

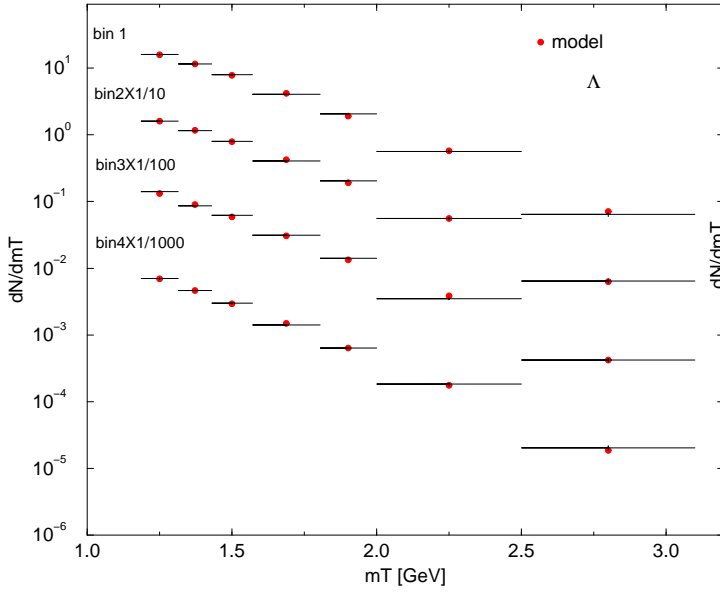


FIG. 6. Thermal analysis  $m_T$  spectra:  $\Lambda$

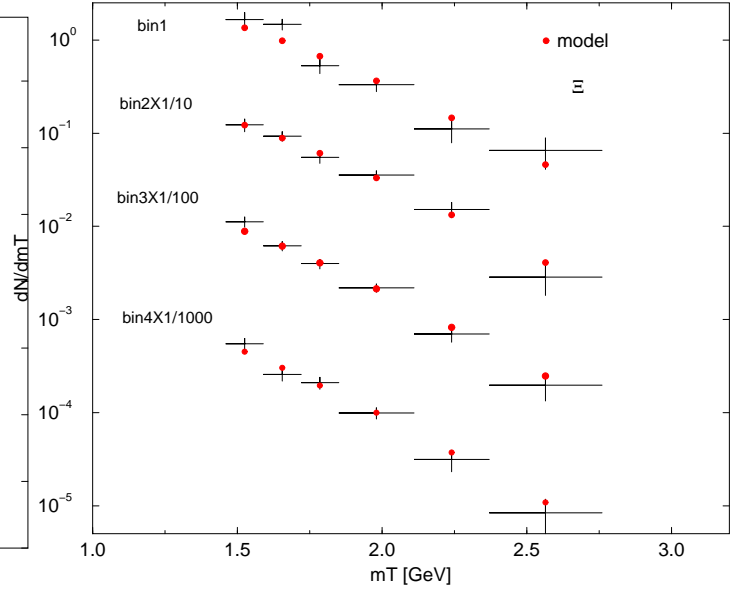


FIG. 8. Thermal analysis  $m_T$  spectra:  $\Xi$

We also describe the  $K_0$  data extremely well, especially in the  $m_\perp$  range which is the same as that for hyperons considered earlier, as is seen in Fig. 10. We recall that these results were obtained reducing the statistical significance of Kaon data, and thus the conclusion is that hyperons predict both the abundance and shape of kaon spectra. Moreover, all the strange hadron spectra can be well described within the model we have adopted.

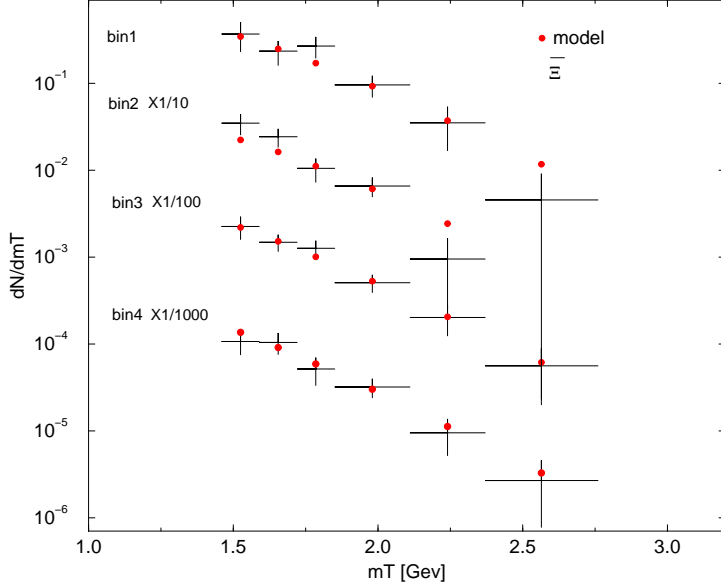


FIG. 9. Thermal analysis  $m_T$  spectra:  $\Xi$

related  $\chi^2_T/DoF$ , the total error divided by degrees of freedom. These are the number of measurements minus number of parameters,  $DoF$  is typically 33 in this data analysis. All curves must have the same  $\chi^2_T/DoF$  at the minimum and this minimum must point to the value of parameters we report. For the temperature  $T$  we produced two results shown in figure 11, in the bottom section for experimental (statistical)  $K^0$  measurement error, and in the top part for the five times enlarged error. We recall that both results are presented in Fig. 1. We note that there is a pronounced  $\chi^2_T/DoF$  minimum shown on logarithmic scale) for all 8 results of which the average value is at  $T = 145$  MeV.

We show in Fig. 12 the profile of  $\chi^2_T/DoF$  for the collective flow velocity  $v$  (top) and the freeze-out surface  $\partial t_f/\partial r_f = 1/v_f$  motion (bottom) being fixed. These minima can be shown on linear scale. We note a mild secondary minimum in the region  $v \simeq 0.25-0.35$ . However, the minima we find at  $v = 0.5-0.58$  are by far more significant.  $\partial t_f/\partial r_f = 1/v_f$  is converging to a sharp minimum seen in bottom portion of Fig. 12 at a value consistent with the sudden breakup scenario. It is necessary to include  $\partial t_f/\partial r_f = 1/v_f$  along with  $v$  in the analysis to find this result, which was not always done in other studies of particle spectra.

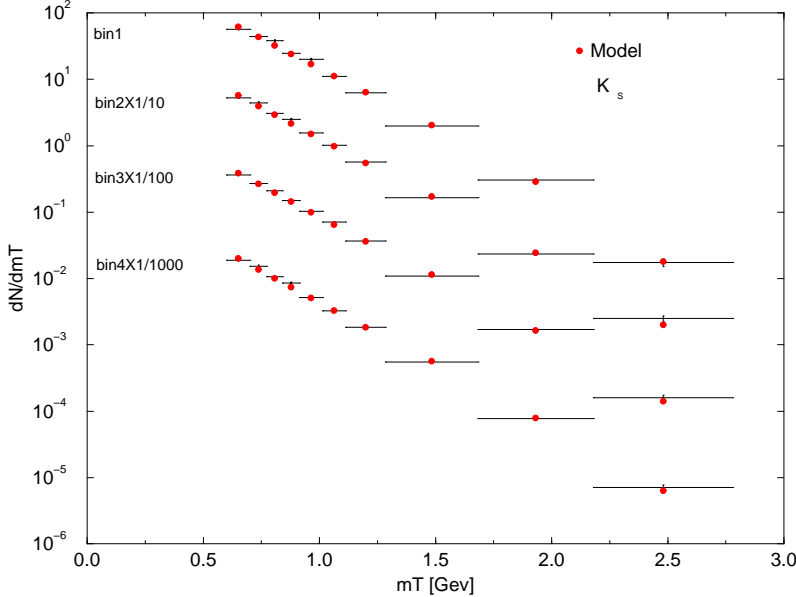


FIG. 10. Thermal analysis  $m_T$  spectra:  $K_s$ .

#### IV. STATISTICAL SIGNIFICANCE OF THE RESULTS PRESENTED

We have analysed the validity and consistency of our data analysis by exploring  $\chi^2/DoF$  profiles. These are obtained by fixing the value of one of the parameters (we consider  $T_f, v, \partial t_f/\partial r_f = 1/v_f$ ), and computing the

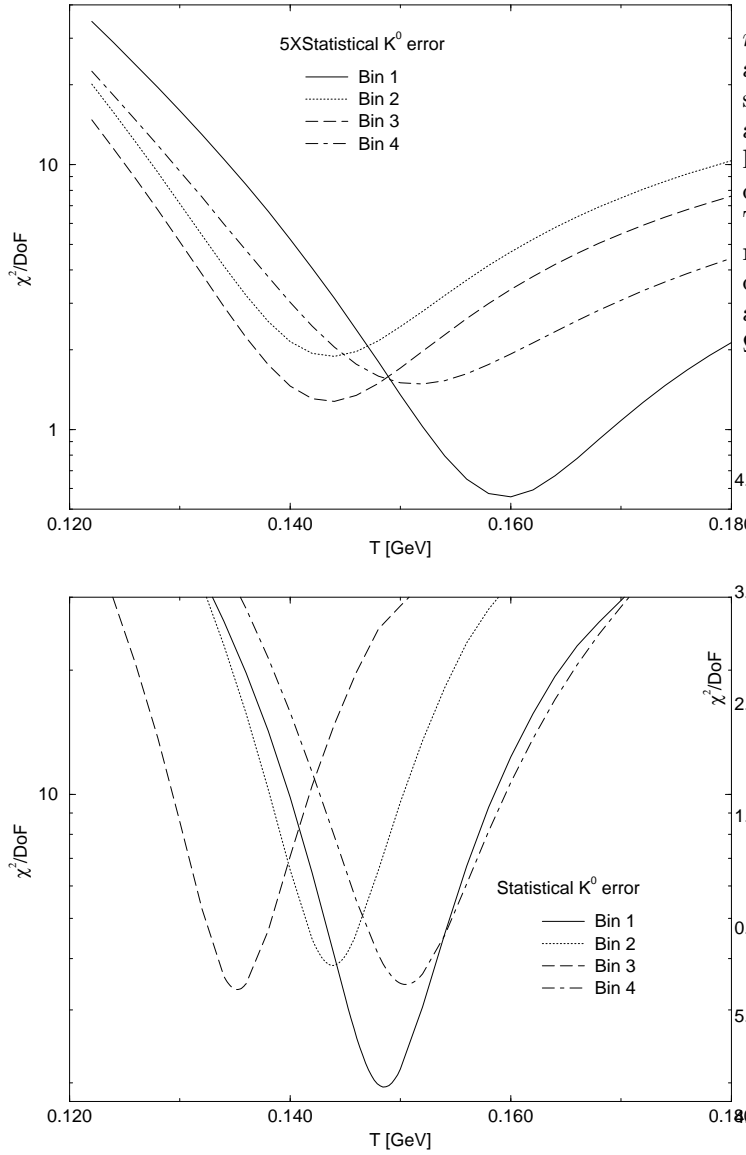


FIG. 11. The total error divided by degrees of freedom for different centrality bins, shown as function of (fixed) freeze-out temperature  $T$ , bottom for the experimental value of the (statistical)  $K^0$  error, top for the 5 times enlarged kaon data statistical errors.

## V. OMEGA SPECTRA

In Fig. 13 all four centrality bins for the sum  $\Omega + \bar{\Omega}$  are shown. We see that we systematically under predict the two lowest  $m_\perp$  data points. Some deviation at high  $m_\perp$  may be attributable to acceptance uncertainties, also seen in the the  $\Xi$  result presented earlier in Fig. 9. We recall that there is a disagreement with the Omega yields in the chemical analysis, which thus does not include in the analysis the production of  $\Omega$ . In the here presented analysis we see that this disagreement is arising at low

momentum.

The low- $m_\perp$  anomaly also explains why the inverse  $m_\perp$  slopes for  $\Omega, \bar{\Omega}$  are smaller than the values seen in all other strange (anti)hyperons. One can presently only speculate about the processes which contribute to this anomaly. We note that the 1-2s.d. deviations in the low  $m_\perp$ -bins of the  $\Omega + \bar{\Omega}$  spectrum translates into 3s.d. deviations from the prediction of the chemical analysis. This is mainly a consequence of the fact that after summing over centrality and  $m_\perp$ , the statistical error which dominates  $\Omega + \bar{\Omega}$  spectra becomes relatively small, and as can be seen the low  $m_\perp$  excess practically doubles the  $\Omega$  yield.

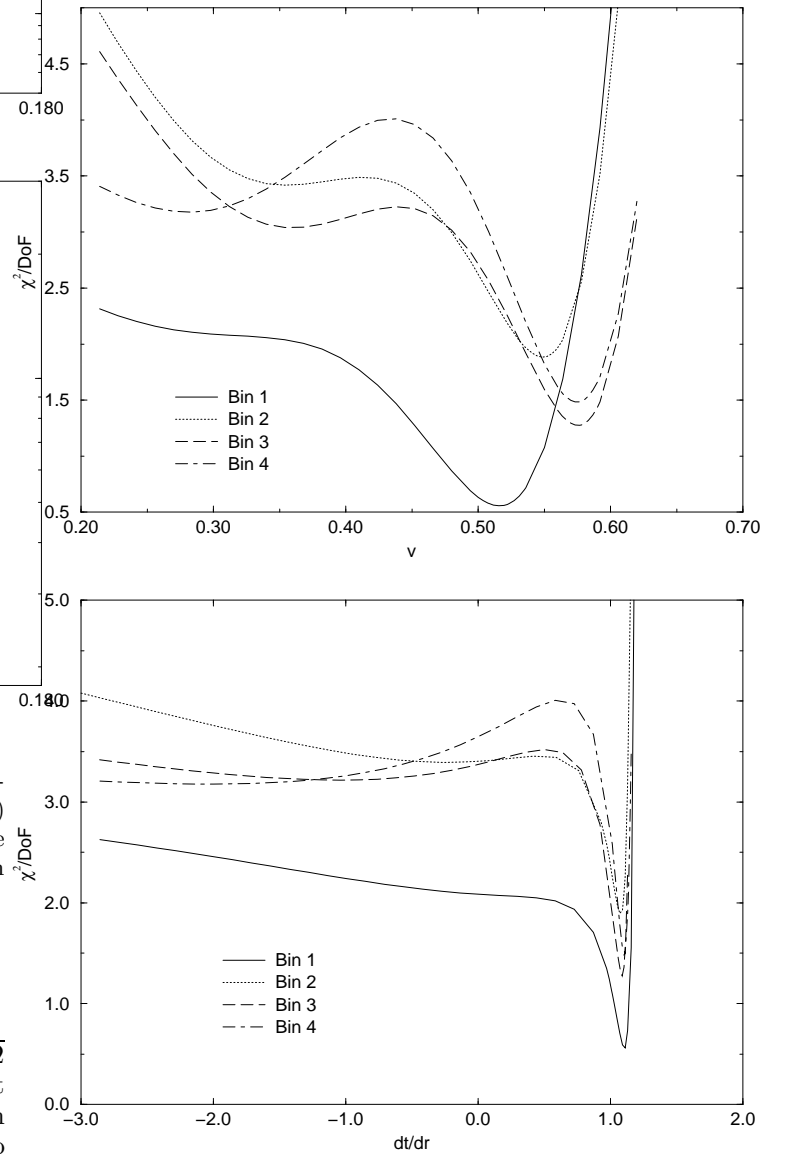


FIG. 12. The total error divided by degrees of freedom for different centrality bins, shown as function of (fixed) flow velocity  $v$  on top and for (fixed) freeze-out surface  $\partial t_f / \partial r_f = 1/v_f$  dynamics on the bottom.



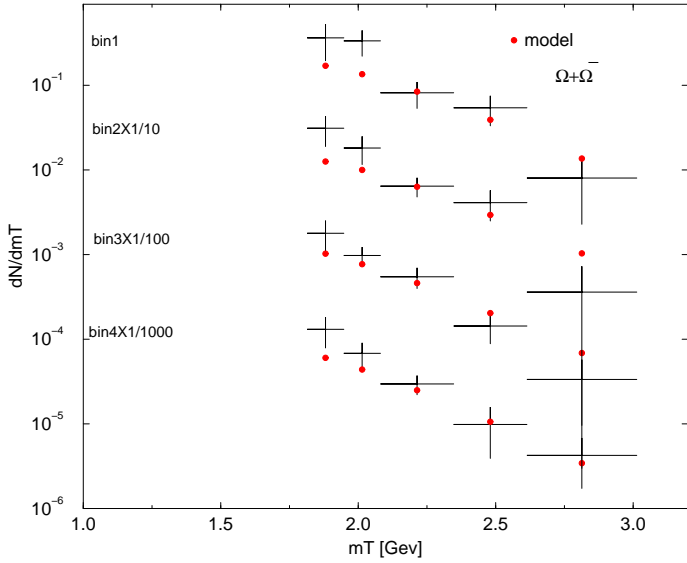


FIG. 13. Thermal analysis  $m_T$  spectra:  $\Omega + \bar{\Omega}$ .

## VI. FINAL REMARKS

Our thermal freeze-out analysis confirms that CERN-SPS results decisively show interesting and new physics, and confirms the reaction picture of a suddenly hadronizing QGP-fireball with both chemical and thermal freeze-out being the same. In our view driven by internal pressure, a quark-gluon fireball expands and ultimately a sudden breakup (hadronization) into final state particles occurs which reach detectors without much, if any, further rescattering. The required sudden fireball breakup arises as the fireball super-cools, and in this state encounters a strong mechanical instability [23]. Note that deep super cooling requires a first order phase transition.

The remarkable similarity of  $m_\perp$  spectra reported by the WA97 experiment is interpreted by a set of freeze out parameters, and we see that production mechanism of  $\Lambda$ ,  $\bar{\Lambda}$ , and  $\Xi$ ,  $\bar{\Xi}$  is the same. This symmetry, including matter-antimatter production is an important cornerstone of the claim that the strange antibaryon data can only be interpreted in terms of direct particle emission from a deconfined phase.

The reader must remember that in presence of conventional hadron collision based physics, the production mechanism of antibaryons is quite different from that of baryons and a similarity of the  $m_\perp$  spectra is not expected. Moreover, even if QGP is formed, but a equal phase of confined particles is present, the annihilation of antibaryons in the baryon rich medium created at CERN-SPS energy would deplete more strongly antibaryon yields, in particular so at small particle momentum, with the more abundant baryons remaining less influenced. This effect is not observed [24].

Similarity of  $m_\perp$ -spectra does not at all imply in our argument a similarity of particle rapidity spectra. As

hyperon are formed at the fireball breakup, any remaining longitudinal flow present among fireball constituents will be imposed on the product particle, thus  $\Lambda$ -spectra containing potentially two original valence quarks are stretched in  $y$ , which  $\bar{\Lambda}$ - $y$ -spectra are not, as they are made from newly formed particles. All told, one would expect that anti-hyperons can appear with a thermal rapidity distribution, but hyperons will not. But both have the same thermal-explosive collective flow controlled shape of  $m_\perp$ -spectra.

We have shown that thermal freeze-out condition for strange hadrons ( $K_s^0$ ,  $\Lambda$ ,  $\bar{\Lambda}$ ,  $\Xi$ ,  $\bar{\Xi}$ ) agrees within error with chemical freeze-out and we have confirmed the freeze-out temperature  $T \simeq 145$  MeV. These findings about the similarity of thermal and chemical freeze-out were controversial, when the experimental single particle spectra were lacking precision, since pion spectra and two particle correlation analysis did not yield this result. However, this paper studies the precise hyperon and kaon  $m_\perp$  spectra which reach to relatively low  $p_\perp$  and compares with definitive chemical analysis of SPS data. The two particle correlation analysis involves pions, which unlike strange hadrons here considered, are potentially witnesses to other physics than the properties of dense and hot quark-gluon phase.

We were able to determine the freeze-out surface  $1/v_f = \partial t_f / \partial r_f$  dynamics and have shown that the break-up velocity  $v_f$  is nearly the velocity of light, as would be expected in a sudden breakup of a QGP fireball. A study with  $\partial t_f / \partial r_f$  has not been previously considered, and only collective flow is included in the description of the particle source. In our analysis we find a slight increase of the transverse expansion velocity with the size of the fireball volume, but consistently  $v \leq 1/\sqrt{3}$ .

We have reproduced the strange particle spectra in all centrality bins. Our findings rely strongly on results obtained by WA97 at smallest accessible particle momentum, and this stresses the need to reach to smallest possible  $p_\perp$  in order to be able to explore the physics of particle freeze-out from the deconfined region. Moreover, we demonstrated that the experimental production data of  $\Omega + \bar{\Omega}$  has a noticeable systematic low  $p_\perp$  enhancement anomaly present in all centrality bins. This result shows that it is not a different temperature of freeze-out of  $\Omega + \bar{\Omega}$  that leads to more enhanced yield, but a soft momentum secondary source which contributes almost equal number of soft  $\Omega + \bar{\Omega}$  compared to the systematic yield predicted by the other strange hadrons.

*Note added:*

We have been made aware by the referee that an analysis of the  $m_\perp$  spectra for high energy collisions has been carried out recently [28]. This work reaches for elementary high energy processes similar conclusions as we have presented regarding the identity of chemical and thermal freeze-out. The higher freeze-out temperature found is also consistent with our results, considering that in nu-

clear collisions significant super cooling occurs [23].

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